The Horizontal Branch of NGC 1851: constraints on the cluster subpopulations

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ABSTRACT

We investigate the distribution of stars along the Horizontal Branch of the Galactic globular cluster NGC 1851, to shed light on the progeny of the two distinct Subgiant Branch populations harbored by this cluster. On the basis of detailed synthetic Horizontal Branch modelling, we conclude that the two subpopulations are distributed in different regions of the observed Horizontal Branch: the evolved stars belonging to the bright Subgiant branch component are confined in the red portion of the observed sequence, whereas the ones belonging to the faint Subgiant branch component are distributed from the blue to the red, populating also the RR Lyrae instability strip. Our simulations strongly suggest that it is not possible to reproduce the observations assuming that the two subpopulations lose the same amount of mass along the Red Giant Branch. We warmly encourage empirical estimates of mass loss rates in Red Giant stars belonging to this cluster.

Subject headings: globular clusters: individual (NGC 1851) — Hertzsprung-Russell diagram – stars: horizontal branch – stars: mass loss

1. Introduction

A recent *HST* ACS photometry of the Galactic globular cluster NGC1851 (Milone et al. 2008 – hereafter M08) has disclosed the existence of two distinct Subgiant branches (SGBs)

in its Color-Magnitude-Diagram (CMD). With this discovery, NGC1851 joins NGC2808 and ω Centauri in the group of globular clusters with a clear photometric signature of multiple stellar populations. M08 estimated an age difference of about 1 Gyr between the two subpopulations, in the assumption that they share the same initial [Fe/H] (spectroscopy of a few Red Giant Branch stars by Yong & Grundahl 2008, together with the narrow RGB sequence in the CMD confirm this assumption), He mass fraction Y and the same metal mixture. Cassisi et al. (2008 – hereafter Paper I) have explored the possibility that one of the two sub-populations was born with a different heavy element mixture (hereafter denoted as extreme) characterized by strong anticorrelations among the CNONa abundances, with a total CNO abundance increased by a factor of 2, compared to the normal α-enhanced metal distribution of the other component (see Sect. 1 and 4 in Paper I for a brief discussion about this choice). Both initial chemical compositions share the same [Fe/H] and Y values. If the faint SGB component (hereafter SGBf subpopulation) has formed with the extreme metal mixture, it results to be coeval with the bright SGB component (hereafter SGBb subpopulation). If the reverse is true, the SGBb (extreme) subpopulation has to be about 2 Gyr younger than the SGBf (normal) one. Following the considerations in Paper I and M08 about the width of Main Sequence and Red Giant Branch (RGB), the slope of the Horizontal Branch (HB) in the cluster CMD, plus the [Fe/H] estimates by Yong and Grundahl (2008), one can also conclude that appreciable variations of the initial He abundance in the two subpopulations are ruled out.

In this paper we have gone a step further, focusing our attention on the HB. Based on the similarity of the number ratio of the SGBb to the SGBf components, with the ratio of stars at the red of the instability strip to stars at the blue side of the strip, M08 hypothesized that the progeny of the two SGBs occupy separate locations along the HB. Here we have addressed this issue in much more detail, analyzing the distribution of stars along the HB by means of synthetic HB models, to determine whether and for which choice of RGB mass loss, the progeny of the SGBb and SGBf subpopulations is able to reproduce the observed HB stellar distribution. We will also readdress the issue, from the point of view of HB modeling, of whether the extreme metal mixture of Paper I is compatible with the observed stellar distribution along the HB. Section 2 describes briefly the HB evolutionary tracks and the HB synthetic modeling, while Sect. 3 presents and discusses the results of our analysis.

2. Synthetic HB modeling

We employed three grids of 39 HB evolutionary tracks each (covering the range between 0.47 and 0.80$M_{\odot}$) all with [Fe/H]=-1.31 (appropriate for NGC1851) calculated by

Pietrinferni et al. (2006) for the normal α-enhanced metal mixture, and from Paper I for the extreme mixture, respectively. For the latter models, two different He abundances have been adopted, namely: Y=0.248 and Y=0.280. The models have been computed using initial He-core masses derived from the evolution of a progenitor with an age of about 12-13 Gyr at the RGB tip. All tracks have been normalized to the same number (450 from the start to the end of central He-burning) of equivalent points [1]; this simplifies the interpolation to obtain tracks for masses not included in the grid.

Figure 1 displays the Zero Age Horizontal Branch (ZAHB) and selected HB tracks for the three chemical compositions considered. The ZAHB for the extreme mixture with enhanced He is much brighter than the case of the normal α-enhanced composition. This makes very difficult the coexistence of sub-populations with these two compositions along the observed HB. The extreme population with the same He abundance of the normal one has a much closer ZAHB brightness, a consequence of similar He-core masses and surface He abundances of their progenitors at the He-flash. Comparisons of HB tracks for selected values of mass display some interesting features. As already shown in Paper I, models for the extreme compositions have a ZAHB location systematically redder than their counterpart with the same mass and a normal composition, but the blue loops during the He-burning phase are more extended (for a given mass). The effect of these differences in terms of mass distribution along the observed HB can be thoroughly assessed only by means of synthetic HB modeling.

Synthetic HBs have been calculated as pioneered by Rood (1973). The observed HB is simulated by a distribution of stars with different mass, that has to be specified as input parameter, together with the time t since each star has first arrived on the HB (and the photometric error, obtained from the photometry). It is assumed that stars are being fed onto the HB at a constant rate. Once the stellar mass and t are specified, a quadratic interpolation in mass among the available tracks and a linear interpolation in time along the track determine the location of the object on the synthetic HB. The large number of points along each of our HB tracks ensures that a linear interpolation in time is adequate. The magnitudes of the synthetic star are then perturbed by a random value for the photometric error in both $F606W$ and $F814W$, according to a Gaussian distribution with dispersion provided by the photometric analysis (the typical value in our case is $\sim$0.01 mag). Either a Gaussian – the standard assumption, see, e.g. Rood (1973), Catelan (1993), Lee et al. (1990) – or a uniform mass distribution is assumed for the objects fed onto the HB, with mean value $\overline{M}$ and dispersion σ as free parameters. This is equivalent to assume that the amount of

[1] See Pietrinferni et al. (2004) for a discussion on this issue

mass lost along the previous RGB phase is stochastic, with a specified unimodal distribution.

Previous analyses of NGC1851, that considered only one stellar population in the cluster, have reached different conclusions about the unimodality of the RGB mass loss. Lee, Demarque & Zinn (1988) were able to reproduce the $B : V : R$ number ratio between stars located at the blue side of the RR Lyrae instability strip, within the strip and at its red side, using a Gaussian mass distribution. Catelan et al. (1998) also conclude that the HB morphology of the cluster can be reproduced with a unimodal (Gaussian) mass distribution, assuming a large 1 σ dispersion (0.055 $M_{\odot}$). On the other hand, Saviane et al. (1998) conclude that a bimodal mass loss is needed to reproduce both the red and blue tails of the observed HB.

In our simulations, we consider two separate components coexisting on the HB, originated from either the SGBb or the SGBf subpopulations. The pairs of values ($\overline{M}$, σ) are left free to vary between the two subpopulations. As a consequence – once the chemical composition of the SGBf and SGBb subpopulations is fixed – one synthetic HB realization is determined by the two pairs of ($\overline{M}$, σ) values chosen for the two components. The reference HB photometry is the HST/ACS ($F606W, F814W$) data by M08. Due to the small number of exposures, M08 could not determine appropriate mean magnitudes for the RR Lyrae population; therefore only stars detected at the blue (143 objects) and red (242 objects) side of the instability strip are taken into account in our comparisons, plus the values of the $B : V : R$ ratios taken from independent data. We assume as reference the values 30 : 10 : 60, obtained from the number counts provided by Catelan et al. (1998), extracted from Walker (1992) photometry. They are consistent with analogous estimates by Lee et al. (1988), Walker (1998) and Saviane et al. (1998). Poisson statistics introduce uncertainties by, respectively, $\pm5\%$, $\pm3\%$ and $\pm8\%$ in the $B : V : R$ values. These ratios also agree with the $B : R$ ratio of $(37 \pm 9) : (63 \pm 7)$ determined by M08 from their CMD.

To be considered a match to the observations, a synthetic HB model is required to satisfy the following constraints: (i) the empirical values of the ratios $B : V : R$; (ii) the $F606W$ and $F814W$ magnitude distribution of the HB stars at the blue and red side of the instability strip; (iii) the number ratio of the progeny of the SGBb to the progeny of the SGBf subpopulations has to satisfy the 55:45 ratio observed along the SGB. In case the two subpopulations share the same age (extreme SGBf component and normal SGBb component) evolutionary times along SGB and RGB are such that the 55:45 ratio is conserved also at the beginning of the HB phase. If the extreme component is 2 Gyr younger (belongs to the SGBb) or both components share the normal composition, population ratios at the beginning of the HB phase are altered by only a few percent, and this is taken into account in our simulations.

In practice, we have first corrected the observed magnitudes and colors of HB stars by the values of reddening ($E(F606W-F814W)$=0.04) and distance modulus ($(m-M)_{F606W}$=15.52) determined in Paper I. The resulting magnitudes have then been used for the comparison with our synthetic models. After selecting the chemical compositions of the two subpopulations – for each SGB component we considered alternatively either a normal or an extreme metal mixture – we calibrated $\overline{M}$ and σ (adopting either a Gaussian or a uniform mass distribution) for their progenies by reproducing the observed $B:V:R$ values, with the additional constraint posed by the ratio between the SGBb and SGBf components. All synthetic stars falling in the gap between the red and blue HB stars selected by M08 are considered to be RR Lyrae variables. We wish to stress that we did not make any a priori choice of where the SGBb and SGBf progenies should be located along the observed HB.

If the $B:V:R$ constraint was satisfied, we finally compared the magnitude distributions of the synthetic red and blue HB, with their observational counterparts, by means of a Kolmogorov-Smirnov (hereafter KS) test, as applied by Salaris et al. (2007) to the analysis of the HB of 47 Tuc. The synthetic HB is considered to be consistent with observations if the KS-test gives a probability below 95% that the observed and synthetic magnitude distributions (in both $F606W$ and $F814W$) for both red and blue HB stars are different. The number of HB stars in the simulations is typically 20 times larger than the observed value in M08 photometry. In this way we minimize, in the synthetic HB model, the effect of statistical fluctuations in the number of objects at a given magnitude and color.

3. Results and discussion

We obtain only one solution for the case where both subpopulations have a normal metal mixture (Model 1) as assumed by M08, and one solution for the case where one the two subpopulations is characterized by the extreme metal mixture (Model 2), i.e. the scenario proposed in Paper I. Figure 2 shows a qualitative comparison between the synthetic HB of Model 2 and the observed one, plus the synthetic star counts of the same simulation (normalized to the observed number of HB stars in M08 photometry) against the observational counterpart. A similar agreement is achieved also for Model 1. The relevant parameters of the two solutions are summarized in Table 1.

Some important conclusions can be drawn from our synthetic HB analysis. First of all, the progeny of the SGBb subpopulation must be restricted to the red part of the HB, whereas the progeny of the SGBf component has to be distributed from the blue to the red, including the whole instability strip, otherwise the KS-test and $B:V:R$ ratios cannot be simultaneously satisfied. As a consequence, it is not possible to reproduce the observed HB

by assuming that RGB stars belonging to the two subpopulations lose on average the same amount of mass. In Model 1 the mass evolving at the RGB tip (in absence of mass loss) for the SGBf component is $0.023M_{\odot}$ smaller than for the SGBb one (following the age estimates in Paper I), whereas the HB modeling requires an upper mass limit smaller by more than $0.035M_{\odot}$ for its progeny. In Model 2 the mass evolving at the RGB tip (in absence of mass loss) for the SGBf sub-population is only $0.003M_{\odot}$ smaller than for the SGBb one, whereas the HB modeling requires a maximum mass $0.054M_{\odot}$ smaller. The observed $B : V : R$ ratios and the KS-analysis impose two further constraints on the model parameters. The mass spread for the red HB stars (the progeny of the SGBb sub-population) has to be small, $\sigma < 0.005M_{\odot}$. On the other hand, a uniform distribution spanning a large mass range is required to reproduce the stellar distributions along the blue part of the observed HB (due to the progeny of the SGBf subpopulation). Although $B : V : R$ ratios can still be reproduced in Model 1 and Model 2 with a Gaussian distribution for the SGBf component ($\overline{M} = 0.605M_{\odot}$ and $\sigma = 0.01M_{\odot}$ for an SGBf population with normal metal mixture, and $\overline{M} = 0.585M_{\odot}$ and $\sigma = 0.01M_{\odot}$ for an extreme metal mixture), the resulting magnitude distributions are at odds with observations.

The results in Table 1 constrain also the relative ages of the SGBb and SGBf subpopulations for the scenario of Paper I. In Model 2 it is the SGBf population that is characterized by the extreme composition; this corresponds to the case discussed in Paper I, where SGBb and SGBf subpopulations share the same age. A SGBb subpopulation with the extreme mixture cannot be accommodated on the HB while at the same time satisfying all empirical constraints described above.

We also considered the case of a 50:50 ratio between the SGBb and SGBf subpopulations, that is still allowed – within the errors on the measured ratio – by M08 data. Synthetic models with the parameter choices of Model 1 and 2 still match the observations (the predicted $B : V : R$ ratios are altered within the errors on the reference values). The mass loss necessary to reproduce the HB must still differ between the two sub-populations. It is also obvious that in this 50:50 scenario an extreme subpopulation can be either the SGBf or the SGBb one (therefore being either coeval or 2 Gyr younger than the normal component) but its progeny has still to populate the extended region from the blue tail of the HB to the red side, otherwise the KS-test is not satisfied.

We have also tested the possibility of having a subpopulation with a mild He-enhanced (Y=0.28) extreme mixture, but no match to the magnitude distribution along the observed HB in the CMD of M08 can ever be achieved.

A different efficiency of mass loss in stars belonging to the same cluster seems difficult to justify, especially if both subpopulations are assumed to share the same metal mixture, but

given the lack of an established theory for the RGB mass loss, we can only use the constraints posed by the HB modeling. If different populations in the same cluster lose different amounts of mass, the second parameter phenomenon in Galactic globulars may well be at least partly due simply to different mass loss efficiencies in different clusters. These conclusions can in principle change if one hypothesizes a multimodal mass loss, or unimodal probability distributions more complex than the standard Gaussian or uniform cases. But more free parameters will have to be included and the predictive power of synthetic HB modeling would be greatly weakened. Overall, our analysis points out that the RGB mass loss in NGC1851 is not simple. Either differential mass loss processes are efficient in stars in the same cluster, or much more complicated probability distributions for the RGB mass loss may have to be employed. Empirical determinations of mass loss rates in NGC1851 stars (see, e.g., the results by Origlia et al. 2007 for 47 Tuc) are badly needed. On this issue, we also wish to note Caloi & D'Antona (2008) recent suggestion that a dispersion in the initial Helium content among the subpopulations within a single cluster can produce the observed HB morphologies, without invoking a large dispersion in the RGB mass loss, or a different mass loss efficiency among the various components. In case of NGC 1851 this scenario seems to be disfavored, raising the intriguing possibility that different processes affecting the early chemical enrichment and RGB mass loss are at work in different clusters.

Before closing we mention an additional test, involving the cluster pulsators. We did not use the constraint posed by their period distribution in our main analysis, because we verified that recent theoretical pulsational models of RR Lyrae stars (Di Criscienzo, Marconi & Caputo 2004 – see also their discussion about uncertainties on the strip boundaries due to the value of the mixing length parameter) predict an instability strip for NGC1851 too red by $\sim$ 0.03-0.04 mag in $(F606W - F814W)$ compared to M08 data. We have made however the following test, considering the periods determined by Walker (1998) for 29 cluster RR Lyraes (all first overtone pulsators have been fundamentalized by adding 0.13 to the logarithm of their periods in days). For all synthetic objects of Model 1 and 2 falling in the observed (not theoretical) RR Lyrae gap we determined the pulsation period from the fundamental pulsation equation by Di Criscienzo et al. (2004 – their Equation 1). The period distribution of the synthetic RR Lyrae stars has been then compared to the observed one by means of a KS-test. Interestingly, we found that Model 1 gives a period distribution inconsistent with observations with a probability larger than 95%, whereas in case of Model 2 this probability is well below the 95% threshold, and we consider this model to have periods statistically in agreement with observations.

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Table 1. Properties of the synthetic models that match the observed HB of NGC 1851

Subpopulation	Mixture	HB coverage	Mass distribution	$B:V:R$
			Model 1	
SGBf	normal	$B+V+R$	Uniform, 0.570 to 0.625 $M_{\odot}$	31:11:58
SGBb	normal	R	Gaussian, $\overline{M}$=0.66 $M_{\odot}$ ($\sigma < 0.005$ $M_{\odot}$)	
			Model 2	
SGBf	extreme	$B+V+R$	Uniform, 0.554 to 0.606 $M_{\odot}$	30:10:60
SGBb	normal	R	Gaussian, $\overline{M}$=0.66 $M_{\odot}$ ($\sigma < 0.005$ $M_{\odot}$)	

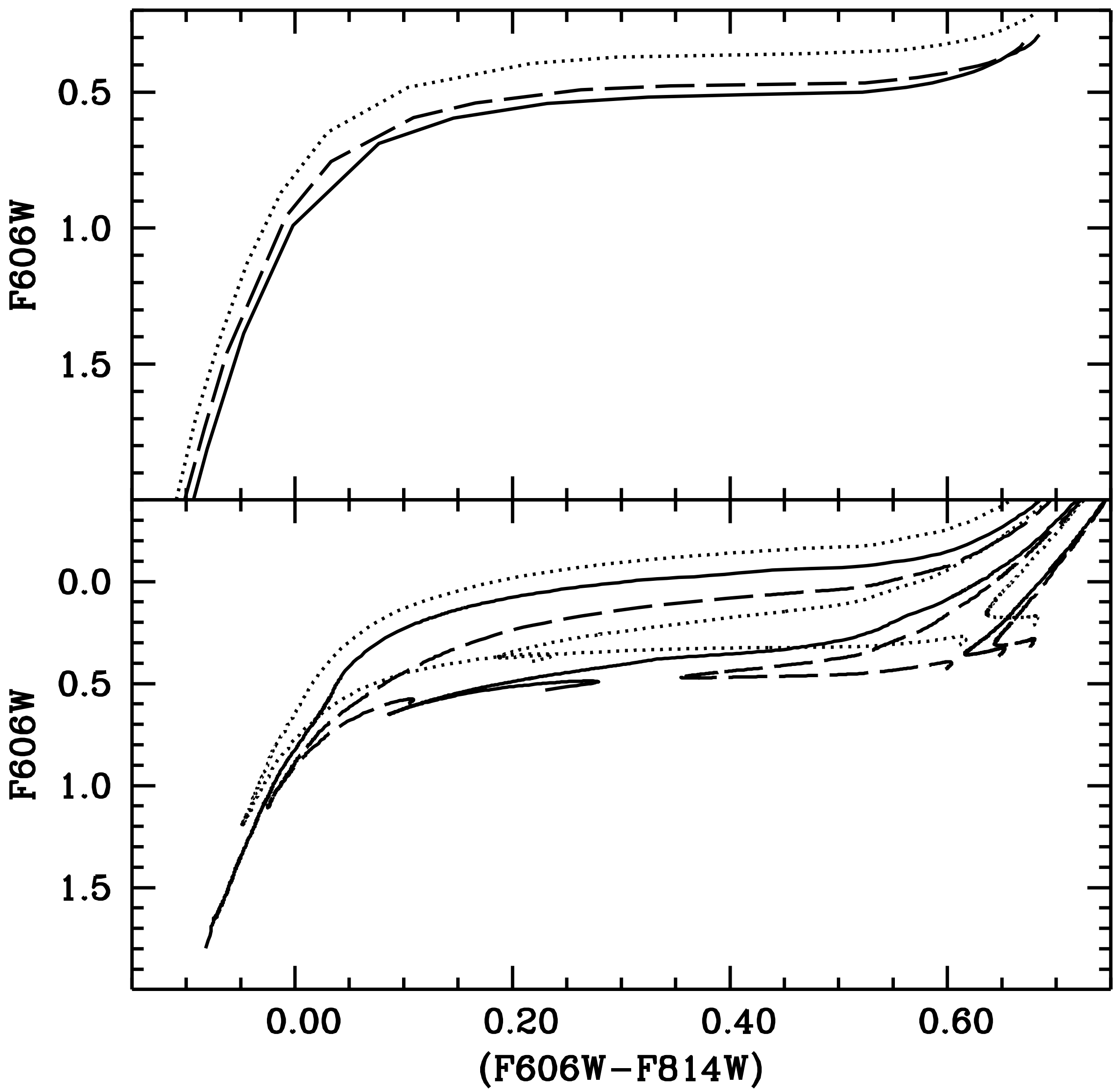

Fig. 1.— Upper panel: ZAHB location in the $F606W - (F606W - F814W)$ plane for, respectively, normal α-enhanced metal mixture with Y=0.248 and [Fe/H]=−1.31 (solid line), extreme mixture with Y=0.248 and [Fe/H]=−1.31 (dashed line), extreme mixture with Y=0.280 and [Fe/H]=−1.31 (dotted line – see text for details). Lower panel: HB evolutionary tracks for masses equal to 0.57, 0.61 and 0.72 $M_{\odot}$, respectively, and the same three chemical compositions as in the upper panel.

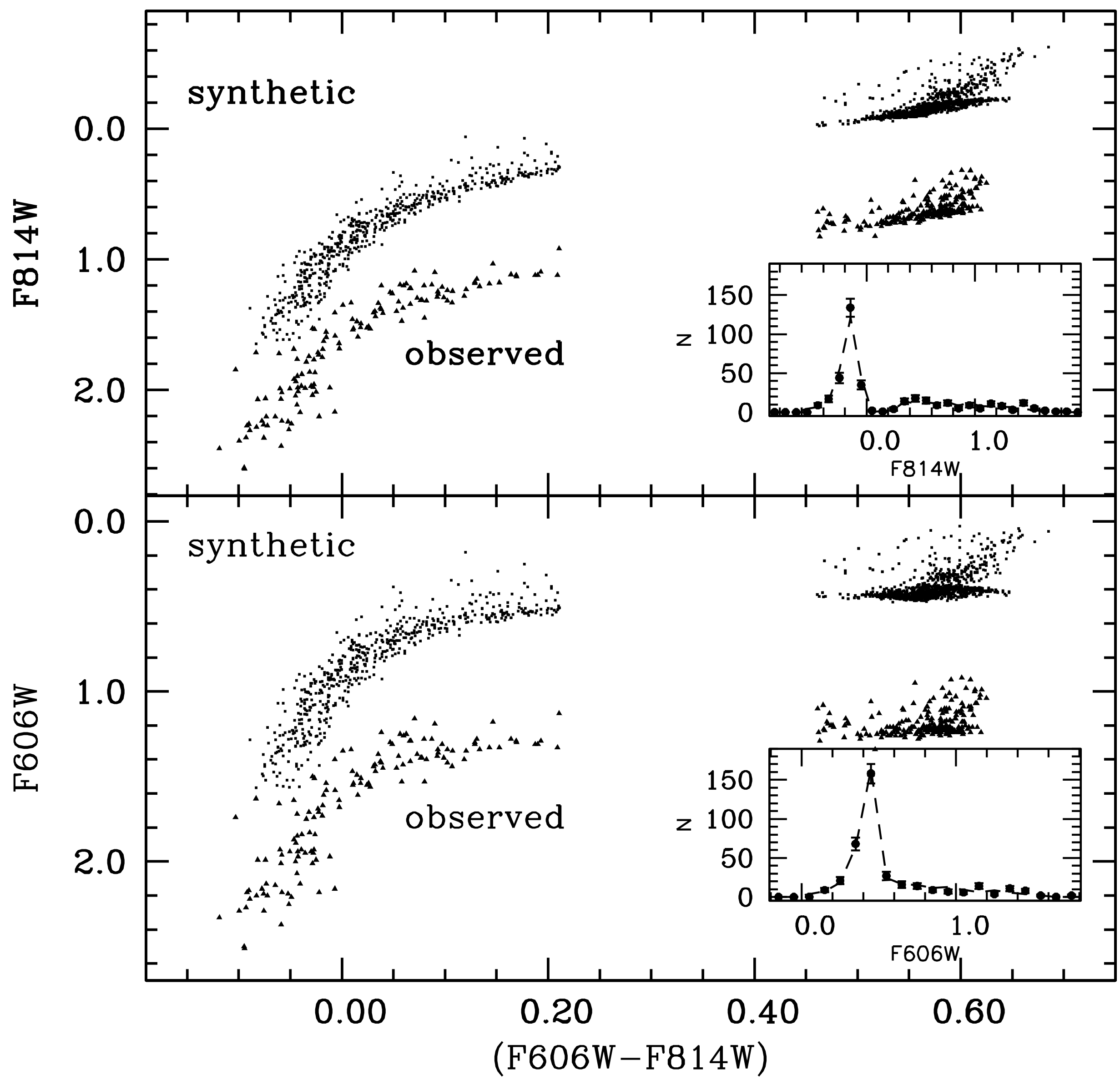

Fig. 2.— Qualitative comparison of the synthetic (Model 2) and observed CMDs of the HB of NGC1851. Observed colors have been corrected for the effect of reddening, whereas the $F606W$ and $F814W$ magnitudes have been shifted arbitrarily for the sake of clarity. A comparison of star counts along the HB is also shown. Model (dashed lines) counts have been rescaled to the same number of observed HB objects. The drop to zero around $F814W$=0 corresponds to the gap at the RR Lyrae instability strip in the $F814W$-$(F606W - F814W)$ CMD.